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# Search for $W' \rightarrow t\bar{b}$ in the lepton plus jets final state in proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV with the ATLAS detector



ATLAS Collaboration\*

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## ABSTRACT

A search for new charged massive gauge bosons, called  $W'$ , is performed with the ATLAS detector at the LHC, in proton–proton collisions at a centre-of-mass energy of  $\sqrt{s} = 8$  TeV, using a dataset corresponding to an integrated luminosity of  $20.3 \text{ fb}^{-1}$ . This analysis searches for  $W'$  bosons in the  $W' \rightarrow t\bar{b}$  decay channel in final states with electrons or muons, using a multivariate method based on boosted decision trees. The search covers masses between 0.5 and 3.0 TeV, for right-handed or left-handed  $W'$  bosons. No significant deviation from the Standard Model expectation is observed and limits are set on the  $W' \rightarrow t\bar{b}$  cross-section times branching ratio and on the  $W'$ -boson effective couplings as a function of the  $W'$ -boson mass using the  $\text{CL}_s$  procedure. For a left-handed (right-handed)  $W'$  boson, masses below 1.70 (1.92) TeV are excluded at 95% confidence level.

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## 1. Introduction

Many approaches to theories beyond the Standard Model (SM) introduce new charged vector currents mediated by heavy gauge bosons, usually called  $W'$ . For example, the  $W'$  boson can appear in theories with universal extra dimensions, such as Kaluza–Klein excitations of the SM  $W$  boson [1–3], or in theories that extend fundamental symmetries of the SM and propose a massive right-handed counterpart to the  $W$  boson [4–6]. Little Higgs theories [7] also predict a  $W'$  boson. The search for a  $W'$  boson decaying to a top quark and a  $b$ -quark explores models potentially inaccessible to searches for a  $W'$  boson decaying into leptons [8–11]. For instance, in the right-handed sector, the  $W'$  boson cannot decay to a charged lepton and a right-handed neutrino if the latter has a mass greater than the  $W'$ -boson mass. Also, in several theories beyond the SM the  $W'$  boson is expected to be coupled more strongly to the third generation of quarks than to the first and second generations [12,13]. Searches for a  $W'$  boson decaying to the  $t\bar{b}$  final state<sup>1</sup> have been performed

at the Tevatron [14,15] in the leptonic top-quark decay channel and at the Large Hadron Collider (LHC) in both the leptonic [16–18] and fully hadronic [19] final states, excluding right-handed  $W'$  bosons with masses up to 2.05 TeV at 95% confidence level (CL).

This Letter presents a search for  $W'$  bosons using data collected in 2012 by the ATLAS detector [20] at the LHC, corresponding to an integrated luminosity of  $20.3 \text{ fb}^{-1}$  from proton–proton ( $pp$ ) collisions at a centre-of-mass energy of 8 TeV. The search is performed in the  $W' \rightarrow t\bar{b} \rightarrow \ell\nu b\bar{b}$  decay channel, where the lepton,  $\ell$ , is either an electron or a muon, using a multivariate method based on boosted decision trees. Right-handed and left-handed  $W'$  bosons, denoted  $W'_R$  and  $W'_L$ , respectively, are searched for in the mass range of 0.5 to 3.0 TeV. A general Lorentz-invariant Lagrangian is used to describe the couplings of the  $W'$  boson to fermions for various  $W'$ -boson masses [21, 22]. The mass of the right-handed neutrino is assumed to be larger than the mass of the  $W'$  boson [23], thus allowing only hadronic decays of the  $W'_R$  boson. In the case of a  $W'_L$  boson, leptonic decays are allowed and, since the signal has the same event signature as SM  $s$ -channel single top-quark production, an interference term between these two processes is taken into account [24].

\* E-mail address: [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch).

<sup>1</sup> For simplicity, the notation “ $t\bar{b}$ ” is used to describe both the  $W'^+ \rightarrow t\bar{b}$  and  $W'^- \rightarrow \bar{t}b$  processes.

## 2. ATLAS detector

Charged particles in the pseudorapidity<sup>2</sup> range  $|\eta| < 2.5$  are reconstructed with the inner detector, which consists of several layers of semiconductor detectors (pixel and microstrip), and a straw-tube transition-radiation tracker, the latter covering  $|\eta| < 2.0$ . The inner tracking detector system is immersed in a homogeneous 2 T magnetic field provided by a superconducting solenoid. The solenoid is surrounded by a hermetic calorimeter that covers  $|\eta| < 4.9$  and provides three-dimensional reconstruction of particle showers. The lead/liquid-argon electromagnetic compartment is finely segmented for  $|\eta| < 2.5$ , where it plays an important role in electron identification. Hadronic calorimetry is provided by a steel/scintillator-tiles calorimeter for  $|\eta| < 1.7$  and by liquid-argon with copper or tungsten absorbers end-cap calorimeters that extend the coverage to  $|\eta| = 4.9$ . Outside the calorimeter, air-core toroids provide the magnetic field for the muon spectrometer. Three stations of precision drift tubes and cathode-strip chambers provide an accurate measurement of the muon track curvature in the region  $|\eta| < 2.7$ . Resistive-plate and thin-gap chambers provide muon triggering capability up to  $|\eta| = 2.4$ .

## 3. Data and simulation samples

The data used for this analysis were recorded using unscaled single-electron and single-muon triggers. After stringent data-quality requirements, the amount of data corresponds to an integrated luminosity of  $20.3 \pm 0.6 \text{ fb}^{-1}$  [25].

The  $W'_R$  and  $W'_L$  signals are generated with MADGRAPH5 [26] using FeynRules [27,28] and the CTEQ6L1 [29] parton distribution function (PDF) set. PYTHIA8 [30] is used for parton showering and hadronisation. Simulated samples are normalised to next-to-leading order (NLO) QCD calculations [22] using  $K$ -factors ranging from 1.15 to 1.35 depending on the mass and handedness of the  $W'$  boson. The model assumes that the  $W'$ -boson coupling strength to quarks,  $g'$ , is the same as for the  $W$  boson:  $g'_R = 0$  and  $g'_L = g$  ( $g'_R = g$  and  $g'_L = 0$ ) for left-handed (right-handed)  $W'$  bosons, where  $g$  is the SM  $SU(2)_L$  coupling. The total width of the left-handed (right-handed)  $W'$  boson increases from 17 to 104 GeV (12 to 78 GeV) for masses between 0.5 and 3.0 TeV, where the decay to leptons is (is not) allowed [21]. In order to account for the effect of the interference between  $W'_L$ -boson and  $s$ -channel single top-quark production dedicated  $pp \rightarrow W'_L/W \rightarrow t\bar{b} \rightarrow \ell\nu b\bar{b}$  samples are simulated, using MADGRAPH5, and assuming a destructive interference term [24]. In addition, samples are generated for values of  $g'/g$  up to 5.0, for several  $W'$ -boson (left- and right-handed) mass hypotheses.

Top-quark pair ( $t\bar{t}$ ) and single top-quark  $s$ -channel and  $Wt$  processes are simulated with the POWHEG [31,32] generator, which uses a NLO QCD matrix element with the CT10 PDFs [29]. The parton shower and the underlying event are simulated using PYTHIA v6.4 [33]. The  $t$ -channel single-top-quark process is modelled using the ACERMC v3.8 [34] generator with the CTEQ6L1 PDFs and PYTHIA v6.4. The  $t\bar{t}$  cross-section is calculated at next-to-next-to-leading order (NNLO) in QCD including resummation of next-to-next-to-leading logarithmic soft gluon terms with TOP++2.0 [35–41]. The single top-quark cross-sections are obtained from

approximate NNLO calculations [42–44]. A top-quark mass of 172.5 GeV is assumed for the production of all simulated processes that include a top quark.

The ALPGEN leading-order multileg generator [45] with the CTEQ6L1 PDFs and PYTHIA v6.4 is used to generate vector bosons in association with jets:  $W$  + jets (including the contributions from  $Wb\bar{b}$  + jets,  $Wc\bar{c}$  + jets and  $Wc$  + jets) and  $Z$  + jets events. Diboson samples ( $WW$ ,  $ZZ$ , and  $WZ$ ), where at least one of the bosons decays leptonically, are modelled using HERWIG v6.52 [46] with the CTEQ6L1 PDFs. The single-boson and diboson simulation samples are normalised to the production cross-sections calculated at NNLO [47,48] and NLO [49] in QCD, respectively.

All generated samples are passed through a full simulation of the ATLAS detector [50] based on GEANT4 [51] and reconstructed using the same procedure as for collision data. Simulated events include the effect of multiple  $pp$  collisions from the same and previous bunch-crossings (in-time and out-of-time pileup) and are re-weighted to match the conditions of the data sample (20.7 interactions per bunch crossing on average).

## 4. Object and event selections

The search for  $W' \rightarrow t\bar{b}$  events relies on the measurement of the following objects: electrons, muons, jets, and the missing transverse momentum. Electrons are identified as energy clusters in the electromagnetic calorimeter matched to reconstructed tracks in the inner detector [52,53]. Electron candidates are required to be isolated, using a fixed cone-size isolation criterion [54], from other objects in the event and from hadronic activity, to reduce the contamination from mis-reconstructed hadrons, electrons from heavy-flavour decays and photon conversions. Electrons are required to have transverse momentum,  $p_T$ , above 30 GeV and  $|\eta| < 2.47$  with a veto on the barrel-endcap transition region in the range  $1.37 < |\eta| < 1.52$ .

Muons are identified using the muon spectrometer and the inner detector [55]. A variable cone-size isolation criterion [54,56] is applied to reduce the contribution of muons from heavy-flavour decays. Muon candidates are required to have  $p_T > 30$  GeV and  $|\eta| < 2.5$ .

Jets are reconstructed using the anti- $k_t$  algorithm [57] with a radius parameter  $R = 0.4$ , using topological energy clusters as inputs [58,59]. Jets are calibrated using energy- and  $\eta$ -dependent correction factors derived from simulation and with residual corrections from in situ measurements [60]. Jets are required to have  $p_T > 25$  GeV and  $|\eta| < 2.5$ . To suppress jets from in-time pileup, at least 50% of the scalar  $p_T$  sum of the tracks associated with a jet is required to be from tracks associated with the primary vertex [61]. This requirement, called the “jet vertex fraction” requirement, is applied only for jets with  $p_T < 50$  GeV and  $|\eta| < 2.4$ . The identification of jets originating from the hadronisation of  $b$ -quarks (“ $b$ -tagging”) is based on properties specific to  $b$ -hadrons, such as long lifetime and large mass. This analysis uses a neural-network-based combination of several high-performance  $b$ -tagging algorithms [62]. The algorithm has an efficiency of 70% (20%, 0.7%) for jets originating from  $b$ -quarks ( $c$ -quarks, light-quark/gluon) as obtained from simulated  $t\bar{t}$  events.

The missing transverse momentum,  $E_T^{\text{miss}}$ , is the modulus of the vector sum of the transverse momentum in calorimeter cells associated with topological clusters, and is further refined with object-level corrections from identified electrons, muons, and jets [63,64]. This analysis requires events to have  $E_T^{\text{miss}} > 35$  GeV to reduce the multijet background.

Candidate events are required to have exactly one lepton and two or three jets with exactly two of them identified as originating from a  $b$ -quark (denoted 2-tag events). The multijet background

<sup>2</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the  $z$ -axis along the beam pipe. The  $x$ -axis points from the interaction point to the centre of the LHC ring, and the  $y$ -axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\text{Ln}(\tan(\theta/2))$ . Observables labelled “transverse” are projected into the  $x$ - $y$  plane.

contribution is further reduced by imposing a requirement on the sum of the  $W$ -boson transverse mass,<sup>3</sup>  $m_T(W)$ , and  $E_T^{\text{miss}}$ :  $m_T(W) + E_T^{\text{miss}} > 60$  GeV. Events with exactly two (three) jets passing all the above selections define the 2-jet (3-jet) channel.

The signal region is defined by selecting events where the reconstructed invariant mass of the  $t\bar{b}$  system,  $m_{t\bar{b}}$  (see definition below), is larger than 330 GeV. The acceptance times efficiency for the  $W' \rightarrow t\bar{b}$  process in the lepton plus jets final state is 5.5%, 2.2% and 2.1% (4.9%, 2.2%, 2.3%) for a  $W'_R$  ( $W'_L$ ) boson with a mass of 1, 2 or 3 TeV, respectively. The drop in acceptance for high  $W'$ -boson masses is due to the lepton failing the isolation criterion and to the decrease of the  $b$ -tagging efficiency. A control region is defined by inverting the requirement on the  $t\bar{b}$  invariant mass,  $m_{t\bar{b}} < 330$  GeV, and is used to derive the normalisation of the  $W$  + jets background.

The method used to reconstruct the invariant mass of the  $t\bar{b}$  system in the selected sample proceeds as follows. The four-momentum of the top quark is reconstructed by adding the four-momenta of the  $W$  boson and of the  $b$ -tagged jet that gives the reconstructed invariant top-quark mass closest to the value used for generation (172.5 GeV). Thereafter, this  $b$ -tagged jet is called the “top-jet” and is assumed to be the  $b$ -jet from the top quark. In this calculation the transverse momentum of the neutrino is given by the  $x$ - and  $y$ -components of the  $E_T^{\text{miss}}$  vector, while the unmeasured  $z$ -component of the neutrino momentum is inferred by imposing a  $W$ -boson mass constraint on the lepton–neutrino system [65]. The four-momentum of the  $t\bar{b}$  system is then reconstructed by adding the four-momenta of the top quark to that of the remaining  $b$ -tagged jet.

## 5. Background estimation

The  $t\bar{t}$ , single-top-quark, diboson and  $Z$  + jets backgrounds are modelled using the simulation and are scaled to the theory predictions of the inclusive cross-sections.

The background originating from multijet events, where a jet is misidentified as a lepton or a non-prompt lepton appears isolated (both referred to as a “fake” lepton), is estimated directly from data using the matrix method [54]. The shape and normalisation of the multijet background are determined in both the electron and muon channels using this method.

The  $W$  + jets background is also modelled using the simulation, but in the case of the 2-jet channel the event yield for this process is derived from data to improve the modelling in this channel. The number of  $W$  + jets events is estimated in the 2-jet control region as the number of data events observed after subtraction of all non- $W$  + jets background sources described above. This estimate is then extrapolated to the 2-jet signal region using the  $W$  + jets simulation. For the 3-jet channel the  $W$  + jets background is scaled to the theory prediction.

## 6. Analysis

The analysis strategy relies on a multivariate approach, based on the boosted decision tree (BDT) method using the framework of TMVA [66], to enhance the separation between the signal and the background. For each jet multiplicity and  $W'$ -boson handedness, a separate BDT is trained in the signal region. For the background, a mixture of top-quark,  $W/Z$  + jets, diboson and multijets samples, all weighted according to their relative abundances, is used. The  $W'$ -boson sample used as signal in the BDT training and testing

phases is chosen at a mass of 1.75 TeV since this gives the best expected exclusion limit on the  $W'$ -boson mass, compared to BDTs trained with other  $W'$ -boson mass samples. This choice also ensures very good separation between the BDT shapes of signal and background for  $W'$ -boson masses of 1 TeV and above. This analysis is thus sensitive to the presence of a signal over a wide mass range.

Ten (eleven) variables with significant separation power are identified in the 2-jet (3-jet) samples for the  $W'$ -boson search. These are used as inputs to the BDTs. The list of variables changes slightly depending on the chirality of the signal.

A set of five variables is common to all four BDTs. Two variables,  $m_{t\bar{b}}$  and the transverse momentum of the reconstructed top quark,  $p_T(t)$ , provide the best separation power among all those considered and are shown in Fig. 1. The other three common variables are: the angular separation<sup>4</sup> between the jet associated with the  $b$ -jet originating from the  $W'$  boson and the top-jet (denoted  $b_t$ ),  $\Delta R(b, b_t)$ ; the transverse energy of the top-jet,  $E_T(b_t)$ , and the aplanarity.<sup>5</sup>

In addition, for the 2-jet channel, the following variables are used: the angular separation between the top-jet and the  $W$  boson,  $\Delta R(b_t, W)$ , and the  $\Delta\eta$  between the lepton and the top-jet,  $\Delta\eta(\ell, b_t)$ . For the case of the right-handed  $W'$ -boson search the following variables are also used: the sphericity; the angular separation between the lepton and the  $b$ -jet originating from the  $W'$  boson,  $\Delta R(\ell, b)$ ; the transverse momentum of the lepton,  $p_T(\ell)$ . For the left-handed  $W'$ -boson search, three different variables are chosen: the angle between the top-jet and the missing transverse momentum,  $\Delta\phi(b_t, E_T^{\text{miss}})$ ; the ratio of the transverse momenta of the top-jet and of the  $b$ -jet originating from the  $W'$  boson,  $p_T(b_t)/p_T(b)$ , and  $m_T(W)$ .

For events with three jets, the following variables are used in addition to the common set of variables:  $\Delta R(\ell, b_t)$ ; the sphericity;  $p_T(b)$ ; the invariant mass of the three jets  $m(b, b_t, j)$ . Two more variables are used, for the right-handed case only:  $p_T(\ell)$  and  $\Delta R(b, W)$ , and for the left-handed case:  $\Delta\phi(b_t, E_T^{\text{miss}})$  and  $p_T(b_t)/p_T(b)$ .

Fig. 2 shows the expected BDT output distributions, normalised to unity, in the signal region for the electron and muon channels combined, for several simulated right-handed  $W'$ -boson samples and for the expected background.

## 7. Systematic uncertainties

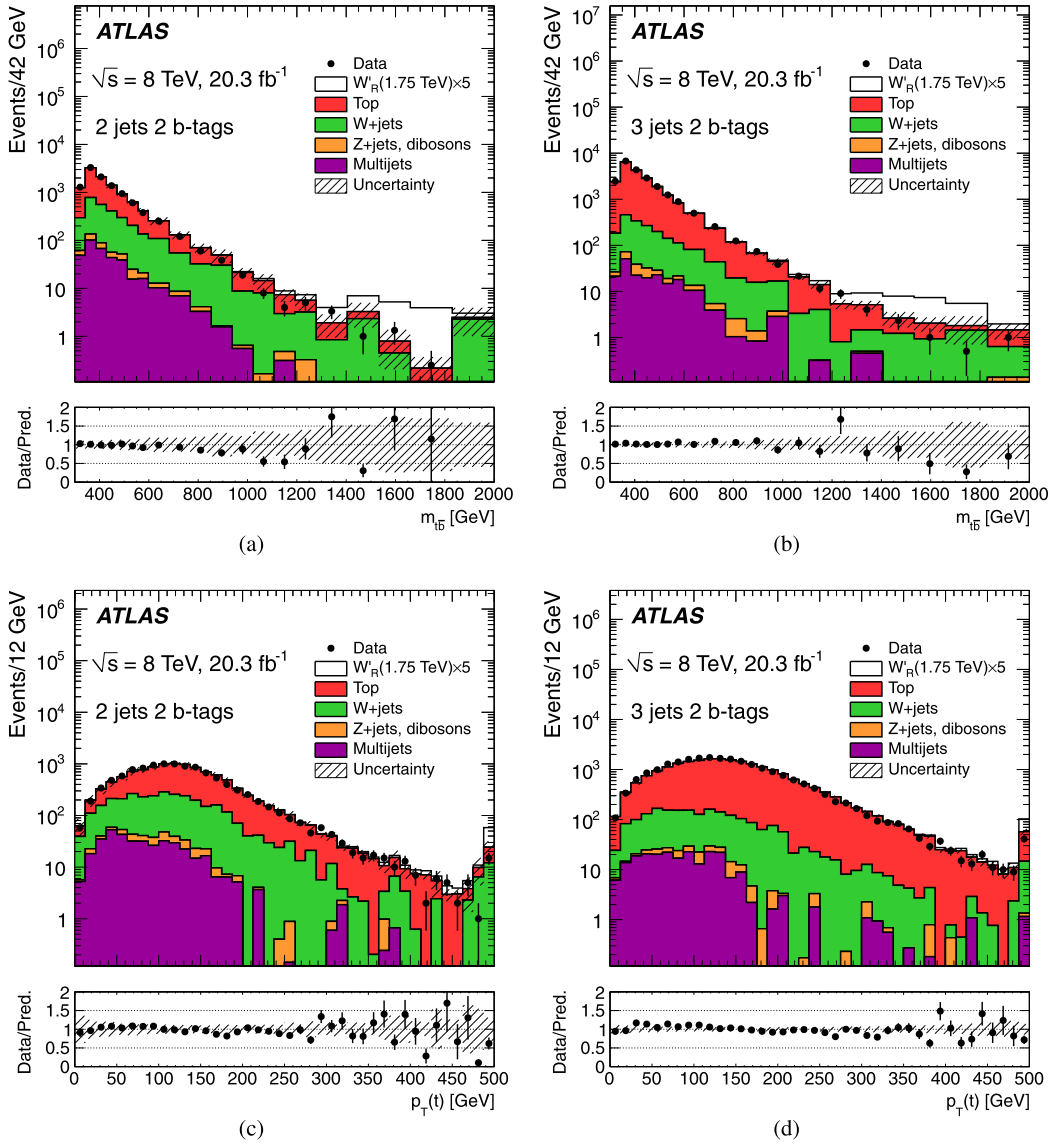
Systematic uncertainties can affect the shape and normalisation of the BDT output distributions. They are split into the categories described below.

**Object modelling:** The main uncertainty in this category is due to uncertainties on  $b$ -tagging efficiency and mistagging rates [68,69]. The resulting uncertainty on the event yield is 6% for the total background contribution and 8–30% for the signal. The large uncertainties on the signal rates are due to additional  $b$ -tagging uncertainties for jets with  $p_T$  above 300 GeV. These uncertainties range from 3% for  $b$ -jets with  $p_T$  of 50 GeV up to 15% at 500 GeV and 35% above. The impact is sizeable for the signal where high- $p_T$  jets stem from the  $W'$ -boson decay, in particular when the  $W'$ -boson mass is above 1 TeV. The jet energy scale uncertainty depends on the  $p_T$  and  $\eta$  of the reconstructed jet and includes the uncertainty on the  $b$ -jet energy scale. It results in an uncertainty on event yields of 1–6% for the signal and 1–4% for the background, depending on the channel. The systematic uncertainty associated with the

<sup>3</sup> Defined as  $m_T(W) = \sqrt{(p_T(\ell) + E_T^{\text{miss}})^2 - (p_x(\ell) + E_x^{\text{miss}})^2 - (p_y(\ell) + E_y^{\text{miss}})^2}$ , where  $E_x^{\text{miss}}$  and  $E_y^{\text{miss}}$  are the  $x$ - and  $y$ -components of the  $E_T^{\text{miss}}$  vector.

<sup>4</sup> Defined as  $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ .

<sup>5</sup> Aplanarity and sphericity are event shape variables calculated from the sphericity tensor of the lepton and jet momenta [67].



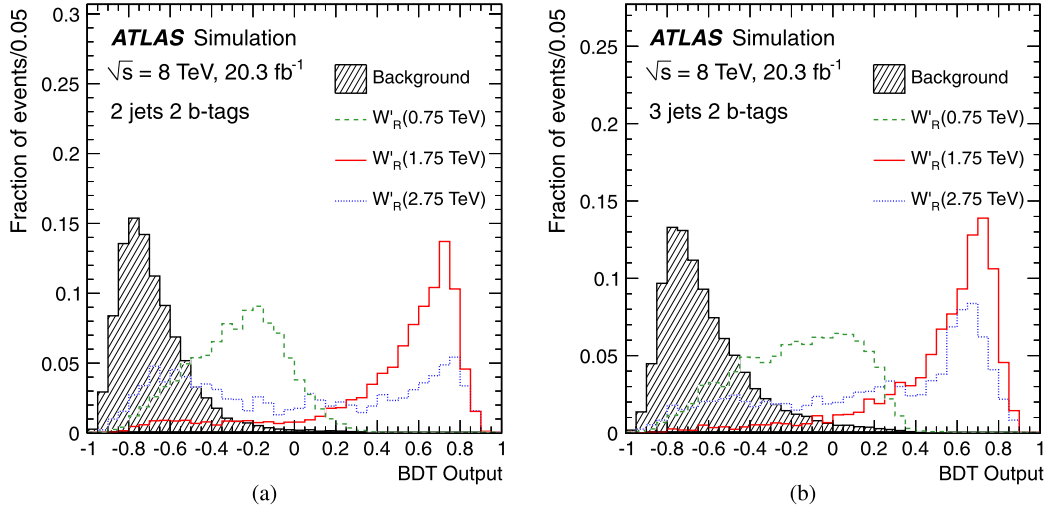
**Fig. 1.** Distribution of, (a) and (b), the reconstructed invariant mass of the  $t\bar{t}$  system and, (c) and (d), of the reconstructed transverse momentum of the top quark, in the signal region for 2-jet and 3-jet events, respectively (electron and muon channels are combined). The process labelled “Top” includes  $t\bar{t}$  production and all three single top-quark production modes. A signal contribution, amplified by a factor of five, corresponding to a  $W_R$  boson with a mass of 1.75 TeV is shown on top of the background distributions. Uncertainty bands include normalisation uncertainties on all backgrounds and the uncertainty due to the limited size of the simulated samples. The last histogram bin includes overflows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

efficiency of the requirement on the jet vertex fraction results in rate variations of 2%. The impact of the jet energy resolution [70] and the jet reconstruction efficiencies on signal and background rates is small. Uncertainties related to lepton energy scale and resolution as well as trigger and identification efficiencies have a total effect of 2–4% on the signal and background rates. Another minor source of uncertainty comes from the propagation of the lepton and jet energy scale and resolution uncertainties to the  $E_T^{\text{miss}}$ . The impact of pileup effects is negligible.

**Simulation modelling:** The dependence of the  $t\bar{t}$  event yield on additional radiation is evaluated by varying PYTHIA parameters, while retaining consistency with a measurement of  $t\bar{t}$  production with additional jet activity [71]. The variation in acceptance due to this source of uncertainty is 6–9%. The dependences of the  $t\bar{t}$ , single top-quark  $s$ -channel and  $Wt$  event yields on the generator and parton showering simulation are estimated by comparing the nominal POWHEG+PYTHIA samples to samples produced using MC@NLO v4.03 [72,73] with the CT10 PDF set and interfaced to HERWIG and

JIMMY v4.31 [74], for simulation of the underlying event and parton shower. For the dominant  $t\bar{t}$  background, the uncertainties arising from the choice of hadronisation and parton shower models are also assessed by a comparison with POWHEG+HERWIG samples. This comparison results in a larger variation of the  $t\bar{t}$  event yields (6–11%) and is thus taken as the associated systematic uncertainty. For the  $t$ -channel single top-quark process, the comparison is performed between the nominal ACERMC+PYTHIA sample and a sample simulated with aMC@NLO v2.1 [75] interfaced to HERWIG. An uncertainty associated with the NLO calculation of  $Wt$  production [76] is evaluated by comparing the baseline sample generated with the diagram removal scheme to a  $Wt$  sample generated with the diagram subtraction scheme. The PDF uncertainty on all signal and background simulated samples is estimated, following the PDF4LHC recommendations [77], by taking the envelope of CT10, MWST2008NLO68CL [78] and NNPDF23 [79] PDF sets uncertainties at 68% CL and normalising to the nominal cross-section. The uncertainties on event yields are 9% for signal





**Fig. 2.** Distributions of the BDT output values for the sum of all background processes (hatched histogram) and for three different mass values of the  $W'_R$ -boson signal (open histograms) in (a) the 2-jet and (b) the 3-jet signal region. Electron and muon channels are combined. All distributions are normalised to unity.

**Table 1**

Impact of the main sources of object and modelling systematic uncertainties on the signal and background event yields (only yield differences above 1% are shown). The quoted modelling uncertainty is on  $t\bar{t}$  yields only.

Source	$W'_R$ (1.75 TeV)	Background
$b$ -tagging efficiency	27%	6%
Jets	4%	1–4%
Lepton	2%	2–4%
$t\bar{t}$ modelling		8–14%
PDF	9%	3–5%

and 3–5% for the total background. The statistical uncertainty due to the limited size of the simulated samples is also taken into account.

**Background normalisation:** Theoretical uncertainties on cross-sections are  $-5.9/+5.1\%$  for the  $t\bar{t}$  process,  $-2.1/+3.9\%$  and  $3.9\%$  for single top-quark production in the  $t$ -channel and  $s$ -channel respectively, and  $6.8\%$  for the  $Wt$  channel process. For the  $W$  + jets background in the 2-jet channel an average total uncertainty of 50% is used as the result of the propagation, in the data-driven method described in Section 5, of the following uncertainties: theoretical uncertainties on  $t\bar{t}$ , single top-quark and  $Z$  + jets/diboson cross-sections, modelling uncertainties of the  $t\bar{t}$  process, uncertainty on the multijet rate, and systematic uncertainties on the jet energy scale and  $b$ -tagging efficiency. The theoretical normalisation uncertainty used in the 3-jet channel is 42%. This estimate is derived from the uncertainty on the inclusive cross-section of  $W$ -boson production [48] (4%) and the uncertainty on the cross-section ratios of  $W$ -boson production associated with  $n + 1$  jets to  $W$ -boson production associated with  $n$  jets [80] (24% per jet, added in quadrature). An uncertainty of 42% is conservatively assigned to the diboson and  $Z$  + jets rates, which represent very small backgrounds. A systematic uncertainty of 50% on the rate of the multijet background is estimated from a study of uncertainties on the efficiencies and fake rates.

**Luminosity:** The uncertainty on the integrated luminosity is 2.8%. It is derived, following the same methodology as that detailed in Ref. [25], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

The impact on the signal and background event yields of the main object and modelling uncertainties is summarised in Table 1.

**Table 2**

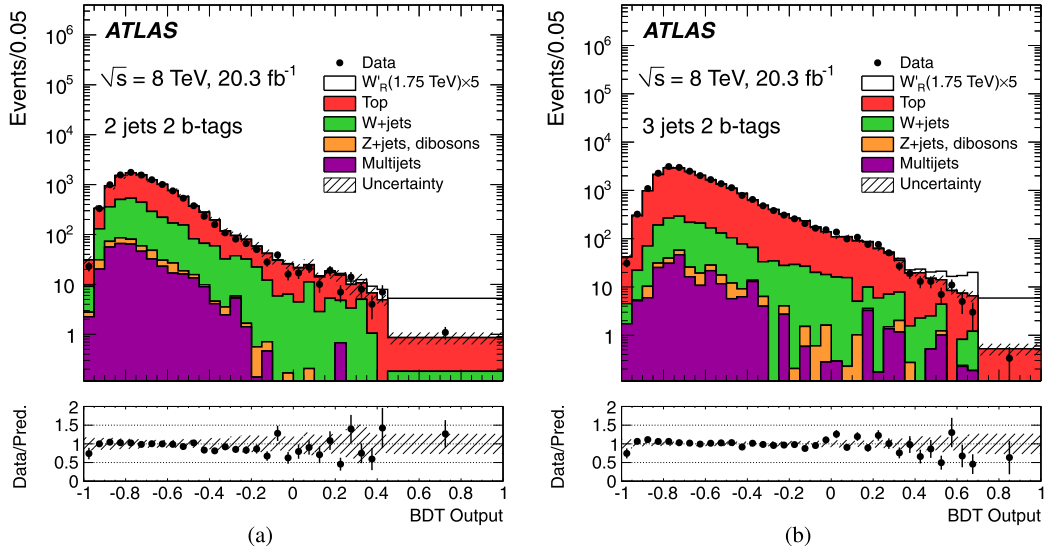
The numbers of expected signal and background events and the numbers of observed data events are shown in the 2-jet and 3-jet signal regions. The quoted uncertainties account for all systematic effects as well as for the statistical uncertainty due to the limited number of events in the simulated samples.

	2-jet 2-tag	3-jet 2-tag
$W'_R$ (0.5 TeV)	$15\,400 \pm 1600$	$9950 \pm 1100$
$W'_R$ (1.0 TeV)	$720 \pm 140$	$800 \pm 140$
$W'_R$ (1.5 TeV)	$49 \pm 15$	$67 \pm 17$
$W'_R$ (2.0 TeV)	$4.9 \pm 1.4$	$7.3 \pm 2.0$
$W'_R$ (2.5 TeV)	$0.8 \pm 0.2$	$1.0 \pm 0.3$
$W'_R$ (3.0 TeV)	$0.26 \pm 0.05$	$0.29 \pm 0.06$
$t\bar{t}$	$6450 \pm 1100$	$17\,700 \pm 2500$
Single-top $t$ -channel	$900 \pm 360$	$1190 \pm 230$
Single-top $Wt$	$320 \pm 50$	$850 \pm 210$
Single-top $s$ -channel	$250 \pm 30$	$137 \pm 20$
$W$ + jets	$2700 \pm 1300$	$1800 \pm 900$
Diboson	$100 \pm 50$	$70 \pm 30$
$Z$ + jets	$17 \pm 7$	$14 \pm 6$
Multijets	$380 \pm 190$	$210 \pm 105$
Total background	$11\,100 \pm 1900$	$22\,000 \pm 3100$
Data	11 039	22 555

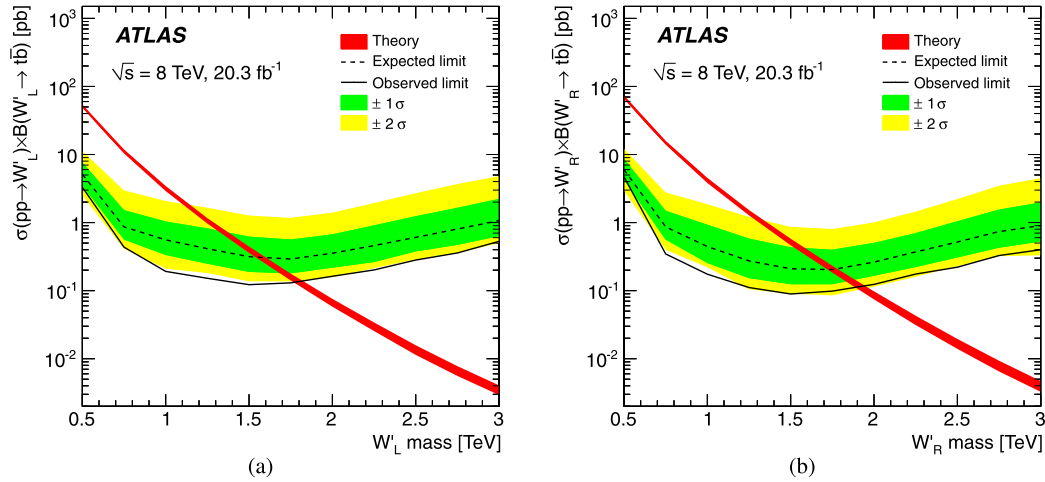
## 8. Results

Table 2 reports the numbers of data events and expected signal and background events for an integrated luminosity of  $20.3 \text{ fb}^{-1}$  in the signal region for 2-jet and 3-jet events, where the electron and muon channels are combined. Fig. 3 shows the BDT output distributions in the signal region. The signal contribution corresponding to a  $W'_R$  boson with a mass of 1.75 TeV is shown, amplified by a factor of five, on top of the background distributions.

No excess in data is observed over the full BDT output distributions. Therefore, the BDT distributions in the 2-jet and 3-jet channels, where electron and muon samples are separated, are used in a combined statistical analysis to calculate exclusion limits on the production cross-section of the left-handed or right-handed  $W'$  boson as a function of its mass. The case of left-handed  $W'$  boson production is treated in two different ways. In the first, the interference between  $W'_L$ -boson and SM  $s$ -channel single top-quark production is neglected. The limits obtained are then valid only for the left-handed signal without the interference contribution. In the second, the interference effect is accounted for by considering the  $pp \rightarrow W'_L/W \rightarrow t\bar{b}$  process as a unique signal and by setting limits



**Fig. 3.** BDT output distributions in the signal region, in (a) 2-jet and (b) 3-jet events (electron and muon channels are combined). The process labelled “Top” includes  $t\bar{t}$  production and all three single top-quark production modes. A signal contribution, amplified by a factor of five, corresponding to a  $W'_R$  boson with a mass of 1.75 TeV is shown on top of the background distributions. The uncertainty band includes normalisation uncertainties on all backgrounds and the uncertainty due to the limited size of the simulated samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 4.** Observed and expected 95% CL limits on the  $W'$ -boson cross-section times branching ratio, as a function of the  $W'$ -boson mass, for (a) left-handed and (b) right-handed  $W'$  bosons. Theoretical predictions of the signal cross-sections [22] (where leptonic decay of the  $W'_R$  boson is not allowed and interference of the  $W'_L$  boson with the  $s$ -channel single top-quark production is not considered) are represented by a solid red line. Theoretical uncertainties, shown as a band, range from about 5% for small  $W'$ -boson masses to 20% for large masses and are dominated by the uncertainty from the CTEQ6.6 [29] NLO PDFs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

on the cross-section of  $W'_L/W \rightarrow t\bar{b}$  production, as a function of the  $W'_L$ -boson mass.

Hypothesis testing is performed with the  $\text{CL}_s$  procedure [81, 82] using a log-likelihood ratio as the test statistic, defined as the ratio of two hypotheses: the test hypothesis, which admits the presence of a  $W'$ -boson signal in addition to the SM backgrounds, and the null hypothesis, which considers only SM backgrounds. For a given hypothesis, the combined likelihood is the product of the likelihoods for the four individual channels considered (2/3-jet and electron/muon samples), each of which is a product of Poisson probabilities over the bins of the BDT output histogram. Pseudo-experiments are generated for both hypotheses, taking into account per-bin statistical fluctuations of the total predictions according to Poisson statistics, as well as Gaussian fluctuations describing the effect of systematic uncertainties. Correlations across bins, channels, and processes are taken into account. In order to reduce the impact of systematic uncertainties on the

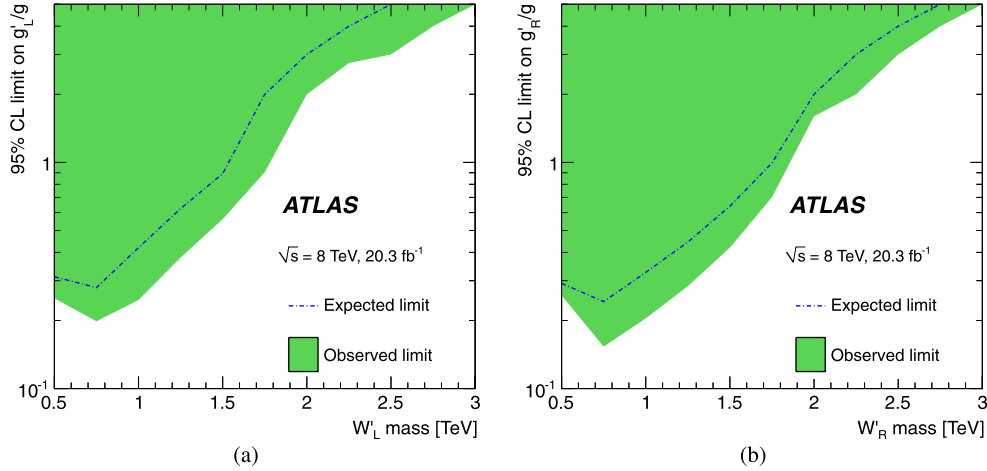
sensitivity of the search, a nuisance parameter corresponding to a scaling factor on the overall  $t\bar{t}$  yield is fitted to data during the statistical analysis. This scaling factor is found to be consistent with unity.

Fig. 4 shows the observed and expected 95% CL limit on the  $W'$ -boson cross-section times branching ratio, as a function of the  $W'$ -boson mass, for left-handed (without the interference term) and right-handed  $W'$ -boson couplings. The fact that the observed limits are lower than expected can be explained by a deficit in data, compared to the predicted number of background events, in the high BDT output region. This deficit is also visible in the tails of the  $m_{t\bar{b}}$  distributions: it is rather localised at 1.1 TeV in 2-jet events, and widespread in 3-jet events (see Fig. 1). In the BDT distributions, however, this deficit is seen mostly at BDT output values higher than 0 in both 2-jet and 3-jet channels, in a region where the  $W'$ -boson distributions peak (for  $W'$ -boson masses of 1 TeV and above). In addition, because of the rather large width of the

**Table 3**

Theoretical cross-section times branching ratio values and observed 95% CL limits for left-handed and right-handed  $W' \rightarrow t\bar{b}$  production (columns two to five) and for  $W'_L/W \rightarrow t\bar{b}$  production, including the interference term (last two columns). In the latter case, results are not shown for  $W'$ -boson masses above 2 TeV due to the lack of  $W'$  events in the  $W'_L/W \rightarrow t\bar{b}$  simulated samples generated at high values of the  $W'$ -boson mass.

$W'$ mass [TeV]	$W'_L \rightarrow t\bar{b}$		$W'_R \rightarrow t\bar{b}$		$W'_L/W \rightarrow t\bar{b}$	
	Theory [pb]	Obs. limit [pb]	Theory [pb]	Obs. limit [pb]	Theory [pb]	Obs. limit [pb]
0.5	52	3.3	70	4.7	53	3.5
1.0	3.2	0.19	4.2	0.17	7.6	0.51
1.5	0.40	0.12	0.52	0.089	5.5	2.0
2.0	0.067	0.16	0.086	0.12	5.4	19
2.5	0.014	0.28	0.017	0.22	–	–
3.0	0.0035	0.53	0.004	0.40	–	–



**Fig. 5.** Observed and expected regions, on the  $g'/g$  vs mass of the  $W'$ -boson plane, that are excluded at 95% CL, for (a) left-handed (no interference) and (b) right-handed  $W'$  bosons.

signal BDT distributions, all  $W'$ -boson cross-section limits are affected by these fluctuations in the data.

The point where the measured cross-section limit crosses the theory curve defines the 95% CL lower limit on the  $W'$ -boson mass. Masses below 1.92 (1.80, 1.70) TeV are excluded for right-handed (left-handed without and with interference)  $W'$  bosons, while the expected limit is 1.75 (1.57, 1.54) TeV. The theoretical cross-section times branching ratio values and the observed limits are reported in Table 3 for several left-handed and right-handed  $W'$ -boson hypotheses.

Limits on the ratio of couplings  $g'/g$  as a function of the  $W'$ -boson mass can be derived from the limits on the  $W'$ -boson cross-section. Limits can also be set for  $g'/g > 1$ , as models remain perturbative up to a ratio of about five [22]. A given hypothesis  $g'$  for a  $W'$  boson of mass  $m_{W'}$  is excluded if the resulting theoretical cross-section is higher than the cross-section limit derived previously. The  $W'$ -boson cross-section has a non-trivial dependence on the coupling  $g'$ , coming from the variation of the resonance width, which is proportional to  $g'^2$ . The scaling of the  $W'$ -boson cross-section as a function of  $g'/g$  and  $m_{W'}$  is estimated using MADGRAPH. The impact of NLO corrections on this scaling is found to be at most a few percent and is neglected. In addition, specific signal samples (see Section 3) are used in order to take into account the effect on the acceptance and on kinematical distributions of the increased signal width (compared to the nominal samples) for values of  $g'/g > 1$ . Fig. 5 shows the observed and expected 95% CL limits on the ratio  $g'/g$ , as a function of  $m_{W'}$ , for left-handed (no interference) and right-handed  $W'$ -boson couplings. The lowest observed (expected) limits on  $g'/g$ , obtained for a  $W'$ -boson mass of 0.75 TeV, are 0.20 (0.28) and 0.16 (0.24) for  $W'_L$  and  $W'_R$ , respectively.

Fig. 6 shows the  $W'$ -boson cross-section limits of Fig. 4 together with the limits obtained by a search for  $W' \rightarrow t\bar{b}$  boson production in the fully hadronic channel [19] performed at  $\sqrt{s} = 8$  TeV with the ATLAS detector.

## 9. Summary

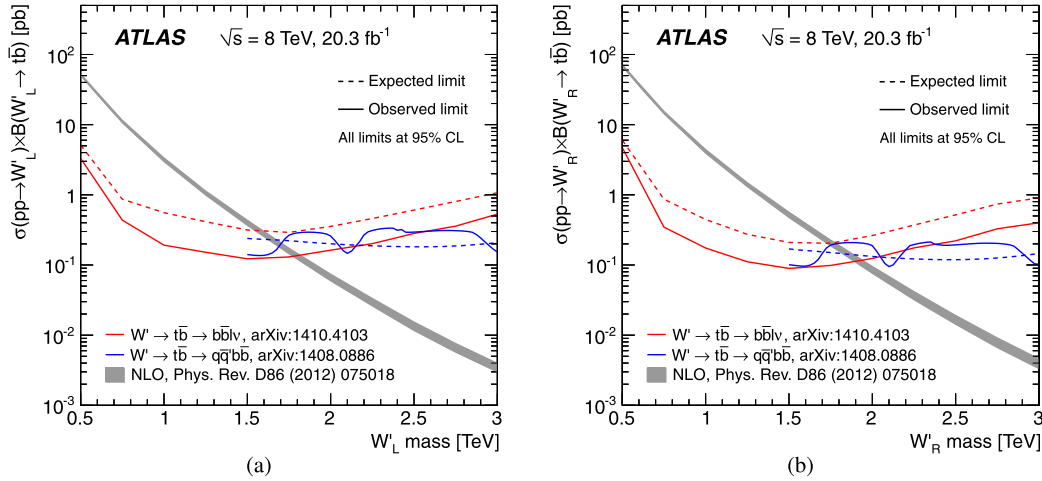
This Letter describes a search for  $W' \rightarrow t\bar{b} \rightarrow \ell\nu b\bar{b}$  in  $20.3 \text{ fb}^{-1}$  of proton–proton collisions at a centre-of-mass energy of  $\sqrt{s} = 8$  TeV with the ATLAS detector at the LHC. Events with a lepton, missing transverse momentum and two  $b$ -tagged jets are selected. Multivariate discriminants are constructed using boosted decision trees. By fitting these discriminants in data to the expectation, the consistency with the Standard Model background hypothesis is tested. The data are consistent with the Standard Model expectation and no evidence of  $W'$ -boson signal events is observed. Exclusion limits at the 95% confidence level are set on the mass of the  $W'$  boson and on its effective couplings. Masses below 1.92 (1.80, 1.70) TeV are excluded for right-handed (left-handed without and with interference)  $W'$  bosons, while the expected limit is 1.75 (1.57, 1.54) TeV. The lowest observed (expected) limits on  $g'/g$ , obtained for a  $W'$ -boson mass of 0.75 TeV, are 0.20 (0.28) and 0.16 (0.24) for left-handed and right-handed  $W'$  bosons.

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**Fig. 6.** Observed and expected 95% CL limits on the  $W'$ -boson cross-section times branching ratio, as a function of the  $W'$ -boson mass, for (a) left-handed and (b) right-handed  $W'$  bosons. Results are shown for the present analysis (red lines) together with the limits obtained by a search for  $W' \rightarrow t\bar{b}$  boson production in the fully hadronic channel [19] (blue lines). Theoretical predictions of the signal cross-sections [22] are represented by a solid grey line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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G. Aad<sup>85</sup>, B. Abbott<sup>113</sup>, J. Abdallah<sup>152</sup>, S. Abdel Khalek<sup>117</sup>, O. Abdinov<sup>11</sup>, R. Aben<sup>107</sup>, B. Abi<sup>114</sup>, M. Abolins<sup>90</sup>, O.S. AbouZeid<sup>159</sup>, H. Abramowicz<sup>154</sup>, H. Abreu<sup>153</sup>, R. Abreu<sup>30</sup>, Y. Abulaiti<sup>147a,147b</sup>, B.S. Acharya<sup>165a,165b,a</sup>, L. Adamczyk<sup>38a</sup>, D.L. Adams<sup>25</sup>, J. Adelman<sup>108</sup>, S. Adomeit<sup>100</sup>, T. Adye<sup>131</sup>, T. Agatonovic-Jovin<sup>13a</sup>, J.A. Aguilar-Saavedra<sup>126a,126f</sup>, M. Agustoni<sup>17</sup>, S.P. Ahlen<sup>22</sup>, F. Ahmadov<sup>65,b</sup>, G. Aielli<sup>134a,134b</sup>, H. Akerstedt<sup>147a,147b</sup>, T.P.A. Åkesson<sup>81</sup>, G. Akimoto<sup>156</sup>, A.V. Akimov<sup>96</sup>, G.L. Alberghi<sup>20a,20b</sup>, J. Albert<sup>170</sup>, S. Albrand<sup>55</sup>, M.J. Alconada Verzini<sup>71</sup>, M. Aleksa<sup>30</sup>, I.N. Aleksandrov<sup>65</sup>, C. 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<sup>1</sup> Department of Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup> Physics Department, SUNY Albany, Albany, NY, United States

<sup>3</sup> Department of Physics, University of Alberta, Edmonton, AB, Canada

<sup>4</sup> (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Gazi University, Ankara; (c) Istanbul Aydin University, Istanbul; (d) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

<sup>5</sup> LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

<sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States

<sup>7</sup> Department of Physics, University of Arizona, Tucson, AZ, United States

<sup>8</sup> Department of Physics, The University of Texas at Arlington, Arlington, TX, United States

<sup>9</sup> Physics Department, University of Athens, Athens, Greece

<sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece

<sup>11</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>12</sup> Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

<sup>13</sup> (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

<sup>14</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway

<sup>15</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States

<sup>16</sup> Department of Physics, Humboldt University, Berlin, Germany

<sup>17</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

<sup>18</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

<sup>19</sup> (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

<sup>20</sup> (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

<sup>21</sup> Physikalisches Institut, University of Bonn, Bonn, Germany

<sup>22</sup> Department of Physics, Boston University, Boston, MA, United States

<sup>23</sup> Department of Physics, Brandeis University, Waltham, MA, United States

<sup>24</sup> (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil

<sup>25</sup> Physics Department, Brookhaven National Laboratory, Upton, NY, United States

<sup>26</sup> (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania

<sup>27</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

<sup>28</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

<sup>29</sup> Department of Physics, Carleton University, Ottawa, ON, Canada

<sup>30</sup> CERN, Geneva, Switzerland

<sup>31</sup> Enrico Fermi Institute, University of Chicago, Chicago, IL, United States

<sup>32</sup> (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

<sup>33</sup> (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Physics Department, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China

<sup>34</sup> Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

<sup>35</sup> Nevis Laboratory, Columbia University, Irvington, NY, United States

<sup>36</sup> Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

<sup>37</sup> (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy

<sup>38</sup> (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

<sup>39</sup> The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

<sup>40</sup> Physics Department, Southern Methodist University, Dallas, TX, United States

<sup>41</sup> Physics Department, University of Texas at Dallas, Richardson, TX, United States

<sup>42</sup> DESY, Hamburg and Zeuthen, Germany

<sup>43</sup> Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

<sup>44</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

<sup>45</sup> Department of Physics, Duke University, Durham, NC, United States

<sup>46</sup> SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

<sup>47</sup> INFN Laboratori Nazionali di Frascati, Frascati, Italy

<sup>48</sup> Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

<sup>49</sup> Section de Physique, Université de Genève, Geneva, Switzerland

<sup>50</sup> (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy

<sup>51</sup> (a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

<sup>52</sup> II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

<sup>53</sup> SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

<sup>54</sup> II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

<sup>55</sup> Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

<sup>56</sup> Department of Physics, Hampton University, Hampton, VA, United States

<sup>57</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States

<sup>58</sup> (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

- <sup>59</sup> Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- <sup>60</sup> <sup>(a)</sup> Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; <sup>(b)</sup> Department of Physics, The University of Hong Kong, Hong Kong; <sup>(c)</sup> Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- <sup>61</sup> Department of Physics, Indiana University, Bloomington, IN, United States
- <sup>62</sup> Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- <sup>63</sup> University of Iowa, Iowa City, IA, United States
- <sup>64</sup> Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
- <sup>65</sup> Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- <sup>66</sup> KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- <sup>67</sup> Graduate School of Science, Kobe University, Kobe, Japan
- <sup>68</sup> Faculty of Science, Kyoto University, Kyoto, Japan
- <sup>69</sup> Kyoto University of Education, Kyoto, Japan
- <sup>70</sup> Department of Physics, Kyushu University, Fukuoka, Japan
- <sup>71</sup> Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- <sup>72</sup> Physics Department, Lancaster University, Lancaster, United Kingdom
- <sup>73</sup> <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- <sup>74</sup> Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- <sup>75</sup> Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- <sup>76</sup> School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- <sup>77</sup> Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- <sup>78</sup> Department of Physics and Astronomy, University College London, London, United Kingdom
- <sup>79</sup> Louisiana Tech University, Ruston, LA, United States
- <sup>80</sup> Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- <sup>81</sup> Fysiska institutionen, Lunds universitet, Lund, Sweden
- <sup>82</sup> Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- <sup>83</sup> Institut für Physik, Universität Mainz, Mainz, Germany
- <sup>84</sup> School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- <sup>85</sup> CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- <sup>86</sup> Department of Physics, University of Massachusetts, Amherst, MA, United States
- <sup>87</sup> Department of Physics, McGill University, Montreal, QC, Canada
- <sup>88</sup> School of Physics, University of Melbourne, Victoria, Australia
- <sup>89</sup> Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- <sup>90</sup> Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- <sup>91</sup> <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano, Italy
- <sup>92</sup> B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- <sup>93</sup> National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- <sup>94</sup> Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
- <sup>95</sup> Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- <sup>96</sup> P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- <sup>97</sup> Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- <sup>98</sup> National Research Nuclear University MEPhI, Moscow, Russia
- <sup>99</sup> D.V. Skobel'syn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- <sup>100</sup> Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- <sup>101</sup> Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- <sup>102</sup> Nagasaki Institute of Applied Science, Nagasaki, Japan
- <sup>103</sup> Graduate School of Science and Kobayashi–Maskawa Institute, Nagoya University, Nagoya, Japan
- <sup>104</sup> <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- <sup>105</sup> Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- <sup>106</sup> Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- <sup>107</sup> Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- <sup>108</sup> Department of Physics, Northern Illinois University, DeKalb, IL, United States
- <sup>109</sup> Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- <sup>110</sup> Department of Physics, New York University, New York, NY, United States
- <sup>111</sup> Ohio State University, Columbus, OH, United States
- <sup>112</sup> Faculty of Science, Okayama University, Okayama, Japan
- <sup>113</sup> Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
- <sup>114</sup> Department of Physics, Oklahoma State University, Stillwater, OK, United States
- <sup>115</sup> Palacký University, RCPTM, Olomouc, Czech Republic
- <sup>116</sup> Center for High Energy Physics, University of Oregon, Eugene, OR, United States
- <sup>117</sup> LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- <sup>118</sup> Graduate School of Science, Osaka University, Osaka, Japan
- <sup>119</sup> Department of Physics, University of Oslo, Oslo, Norway
- <sup>120</sup> Department of Physics, Oxford University, Oxford, United Kingdom
- <sup>121</sup> <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- <sup>122</sup> Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
- <sup>123</sup> Petersburg Nuclear Physics Institute, Gatchina, Russia
- <sup>124</sup> <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- <sup>125</sup> Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
- <sup>126</sup> <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; <sup>(b)</sup> Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Department of Physics, University of Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); <sup>(g)</sup> Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- <sup>127</sup> Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- <sup>128</sup> Czech Technical University in Prague, Praha, Czech Republic
- <sup>129</sup> Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- <sup>130</sup> State Research Center Institute for High Energy Physics, Protvino, Russia
- <sup>131</sup> Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>132</sup> Ritsumeikan University, Kusatsu, Shiga, Japan
- <sup>133</sup> <sup>(a)</sup> INFN Sezione di Roma; <sup>(b)</sup> Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- <sup>134</sup> <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy

- <sup>135</sup> <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- <sup>136</sup> <sup>(a)</sup> Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; <sup>(b)</sup> Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; <sup>(c)</sup> Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; <sup>(d)</sup> Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; <sup>(e)</sup> Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
- <sup>137</sup> DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- <sup>138</sup> Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
- <sup>139</sup> Department of Physics, University of Washington, Seattle, WA, United States
- <sup>140</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- <sup>141</sup> Department of Physics, Shinshu University, Nagano, Japan
- <sup>142</sup> Fachbereich Physik, Universität Siegen, Siegen, Germany
- <sup>143</sup> Department of Physics, Simon Fraser University, Burnaby, BC, Canada
- <sup>144</sup> SLAC National Accelerator Laboratory, Stanford, CA, United States
- <sup>145</sup> <sup>(a)</sup> Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- <sup>146</sup> <sup>(a)</sup> Department of Physics, University of Cape Town, Cape Town; <sup>(b)</sup> Department of Physics, University of Johannesburg, Johannesburg; <sup>(c)</sup> School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- <sup>147</sup> <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> The Oskar Klein Centre, Stockholm, Sweden
- <sup>148</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden
- <sup>149</sup> Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
- <sup>150</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- <sup>151</sup> School of Physics, University of Sydney, Sydney, Australia
- <sup>152</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>153</sup> Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- <sup>154</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- <sup>155</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- <sup>156</sup> International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- <sup>157</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- <sup>158</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- <sup>159</sup> Department of Physics, University of Toronto, Toronto, ON, Canada
- <sup>160</sup> <sup>(a)</sup> TRIUMF, Vancouver, BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto, ON, Canada
- <sup>161</sup> Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- <sup>162</sup> Department of Physics and Astronomy, Tufts University, Medford, MA, United States
- <sup>163</sup> Centro de Investigaciones, Universidad Antonio Nariño, Bogotá, Colombia
- <sup>164</sup> Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
- <sup>165</sup> <sup>(a)</sup> INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- <sup>166</sup> Department of Physics, University of Illinois, Urbana, IL, United States
- <sup>167</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- <sup>168</sup> Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- <sup>169</sup> Department of Physics, University of British Columbia, Vancouver, BC, Canada
- <sup>170</sup> Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
- <sup>171</sup> Department of Physics, University of Warwick, Coventry, United Kingdom
- <sup>172</sup> Waseda University, Tokyo, Japan
- <sup>173</sup> Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- <sup>174</sup> Department of Physics, University of Wisconsin, Madison, WI, United States
- <sup>175</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- <sup>176</sup> Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- <sup>177</sup> Department of Physics, Yale University, New Haven, CT, United States
- <sup>178</sup> Yerevan Physics Institute, Yerevan, Armenia
- <sup>179</sup> Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

<sup>a</sup> Also at Department of Physics, King's College London, London, United Kingdom.

<sup>b</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

<sup>c</sup> Also at Novosibirsk State University, Novosibirsk, Russia.

<sup>d</sup> Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

<sup>e</sup> Also at TRIUMF, Vancouver, BC, Canada.

<sup>f</sup> Also at Department of Physics, California State University, Fresno, CA, United States.

<sup>g</sup> Also at Tomsk State University, Tomsk, Russia.

<sup>h</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

<sup>i</sup> Also at Università di Napoli Parthenope, Napoli, Italy.

<sup>j</sup> Also at Institute of Particle Physics (IPP), Canada.

<sup>k</sup> Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

<sup>l</sup> Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

<sup>m</sup> Also at Louisiana Tech University, Ruston, LA, United States.

<sup>n</sup> Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

<sup>o</sup> Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.

<sup>p</sup> Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

<sup>q</sup> Also at CERN, Geneva, Switzerland.

<sup>r</sup> Also at Ochanai Academic Production, Ochanomizu University, Tokyo, Japan.

<sup>s</sup> Also at Manhattan College, New York, NY, United States.

<sup>t</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

<sup>u</sup> Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.

<sup>v</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

<sup>w</sup> Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.

<sup>x</sup> Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.

<sup>y</sup> Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.

<sup>z</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

- <sup>aa</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland.
- <sup>ab</sup> Also at International School for Advanced Studies (SISSA), Trieste, Italy.
- <sup>ac</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
- <sup>ad</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
- <sup>ae</sup> Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
- <sup>af</sup> Also at National Research Nuclear University MEPhI, Moscow, Russia.
- <sup>ag</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- <sup>ah</sup> Also at Department of Physics, Oxford University, Oxford, United Kingdom.
- <sup>ai</sup> Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
- <sup>aj</sup> Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.
- <sup>ak</sup> Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
- <sup>al</sup> Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
- \* Deceased.